COMPUTATIONAL BIOMECHANICAL MODELS OF SQUAT EXERCISE PERFORMED ON THE ADVANCED RESISTIVE EXERCISE DEVICE (ARED)

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National Aeronautics and Space Administration

BACKGROUND

NASA's Digital Astronaut Project (DAP) Vision

The Digital Astronaut Project implements well-vetted computational models to predict and assess spaceflight health and performance risks, and enhance countermeasure development, by

- Partnering with subject matter experts to inform HRP knowledge gaps and countermeasure development decisions;
- Modeling and simulating the adverse physiologic responses to exposure to reduced gravity and analog environments; and
- Ultimately providing timely input to mission architecture and operations decisions in areas where clinical data are lacking.

HRP Risks/Gaps Addressed by This Effort

Risk of Muscle Atrophy: impaired performance due to reduced muscle mass, strength and endurance

- **Gap M7:** Can the current in-flight performance be maintained with reduced exercise volume?
- **Gap M8:** What is the minimum exercise regimen needed to maintain fitness levels for tasks?
- **Gap M9:** What is the minimum set of exercise hardware needed to maintain those fitness levels?

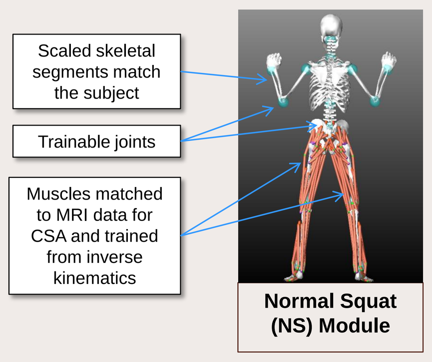
Risk of Loss of Bone Mineral Density: early onset of osteoporosis and bone fracture

- **Osteo 7:** We need to identify options for mitigating early onset osteoporosis before, during and after spaceflight. *(formerly Gap B15)*
- **Osteo 6:** How do skeletal changes due to spaceflight modify the terrestrial risk of osteoporotic fractures? *(formerly Gap B1)*

METHODS: BIO-MECH., ARED & INTEGRATED MODULES

Biomechanical Modules[1,6,10,11]
(GRC and Wyle S.T.&E.)

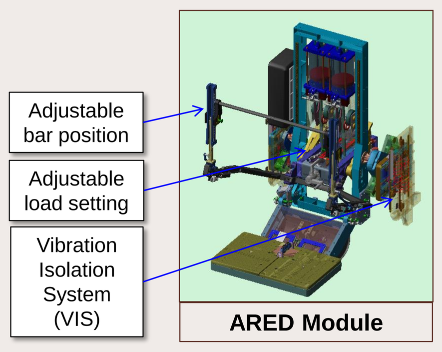
- Derived from motion capture (MoCap) and ground reaction force (GRF) data acquired on the ARED ground unit using an exercise-experienced male subject
- Constructed a forward dynamics module in LifeMOD® (a plug-in to Adams™) during the performance of a 1-repetition maximum squat exercise
- Joint-only and joint/muscle configurations



Normal Squat (NS) Module

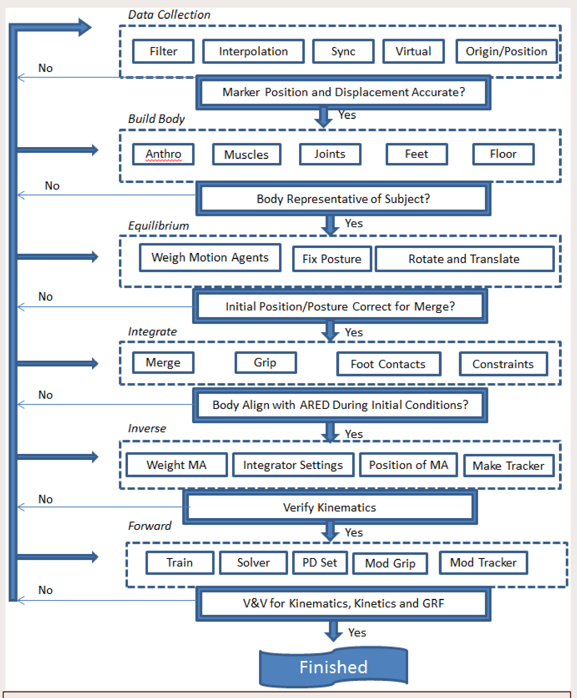
ARED Device Module[2,7]
(ZIN Technologies)

- ARED is a resistance-training exercise device for the crew of the International Space Station (ISS)
- Rigid Body Dynamics module developed using Pro-E solid model files, engineering specifications, and engineering hardware verification data.
- Constructed in MSC Adams™

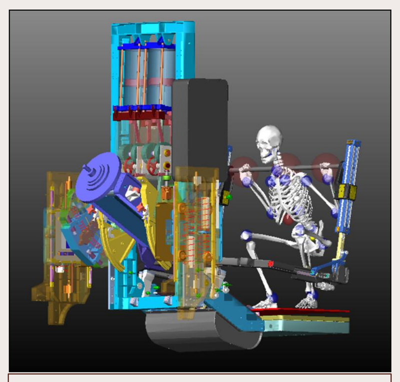


ARED Module

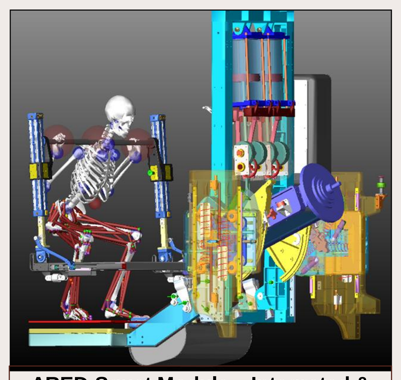
Integrated ARED Squat Modules[7,8,10,11]
(NASA GRC)



Integration Process



ARED Squat Module – Integrated (ASM-i, Trained joints only)



ARED Squat Module – Integrated & with Muscles (ASM-im)

METHODS: IMPLEMENTATION DETAILS

Integration in LifeMOD

- Prior to model merge operation
  - Preset ARED exercise bar to squat configuration
  - Align reference frames of ARED and biomechanical modules
- Balancing of GRF's (vs. measured GRF data) iteratively determines proper co-alignment of the modules
- Visual inspection of model posture used to verify results of equilibrium analysis
- Motion capture marker weights are adjusted to obtain proper posture
- Physical contacts modeled as below

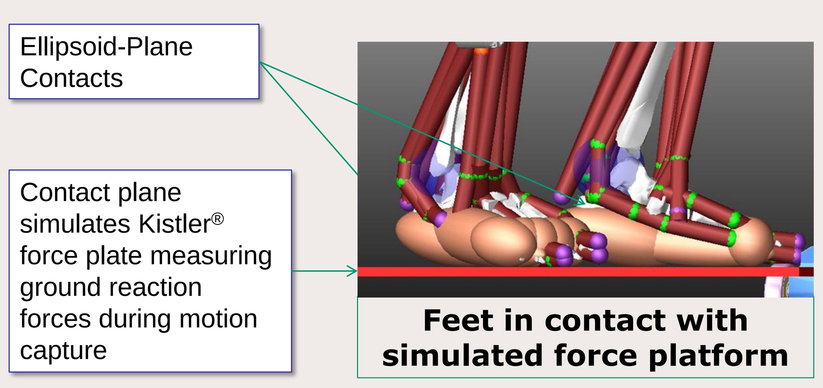
Joint and Muscle Training

- Adjustable parameters
  - Servo joints
    - Proportional gain
    - Derivative gain
  - Passive joints
    - Translational Stiffness/Damping
    - Rotational Stiffness/Damping
  - Muscles
    - Stiffness
    - Damping
    - Phys. Cross Sectional Area (matches MRI data)
    - Tone
    - PID gains
    - Insertion geometry

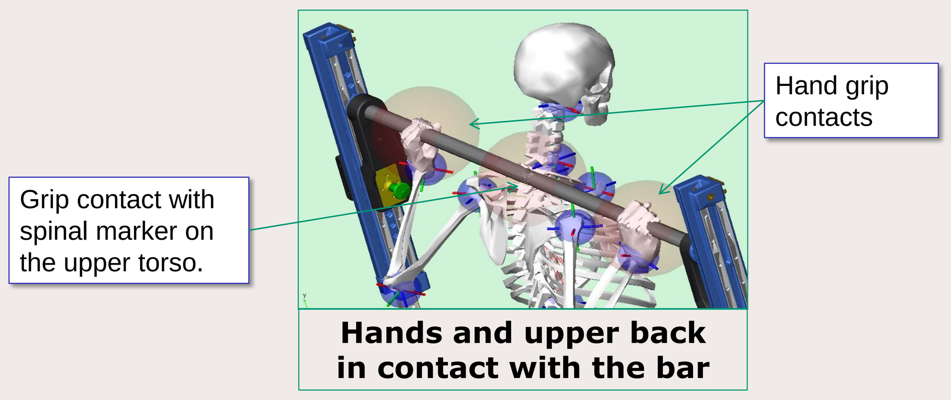
Other Steps

- Motion tracker agent
  - Residual forces applied at pelvis in transverse directions to keep the model stable during the exercise
  - Adjustable rotational and translational stiffness
- GRF data and joint angle errors iteratively verify the forward dynamics simulations
  - With ARED
  - Without ARED – compare to existing biomechanical models
  - Adjust gain and stiffness /damping until model is verified

Modeling of Contacts Between Biomechanical Module and ARED



Feet in contact with simulated force platform



Hands and upper back in contact with the bar

VERIFICATION AND VALIDATION (V&V)

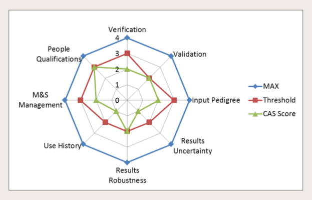
Verification: Is the model constructed correctly?

- Compare joint angles and displacements between the forward dynamics (driven by the trained module) with inverse dynamics (driven by MoCap data)
- Vary the load setting on the ARED module and examine the resulting forces, muscle tensions and joint torques

Validation: Are the model results meaningful?

- Compare calculated forces, muscle tensions and joint torques with reported measurements in the literature made under similar loading conditions.
- Conform to NASA-STD-7009 standards for assessing the credibility of computational models in all V&V activities

Results of V&V of ASM-im in 1g per NASA-STD-7009[9]



Legend	
Blue	CAS Score > Threshold
Green	Threshold ≥ CAS Score ≥ (Threshold-0.5)
Yellow	(Threshold-0.5) > CAS Score ≥ (Threshold-1.0)
Red	CAS Score < (Threshold-1.0)

	CAS Score	Overall Weight	Overall Credibility	Thresholds	MAX
Verification	2	0.4	1.8	3	4
Validation	2	0.5		2	4
Input Pedigree	2	0.2		3	4
Results Uncertainty	1	0.1		2	4
Results Robustness	2	0.2		2	4
Use History	1	0.15		2	4
M&S Management	2	0.1		3	4
People Qualifications	3	0.15		3	4

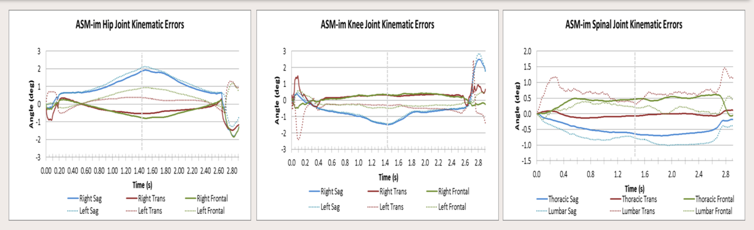
- V&V Scores for 1g models
  - 1.8 for ASM-I
  - 1.5 for ASM-im
- Preliminary 0g assessments
  - 1.4 for ASM-I
  - 1.1 for ASM-im,
  - Lower use history and robustness scores in 0g.

RESULTS: MUSCLE AND JOINT-ONLY MODULES

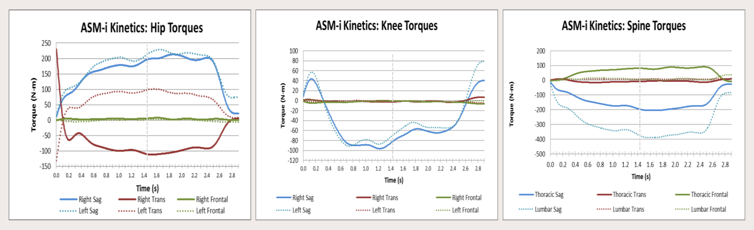
Joint Data

- Key joints of interest:, Hip, Knee, Thoracic Spine and Lumbar Spine

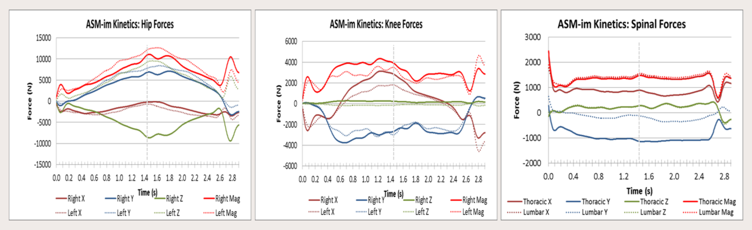
Joint Angle Errors
- Differences in joint angles between forward and inverse dynamics
- Indicate imperfections in the ability of the forward module to exactly duplicate the kinematics
- <2 deg error during key phases of the squat movement



Joint Torques
- Calculated moments at key joints in primary planes of interest
- Indicate the dynamics of the movement



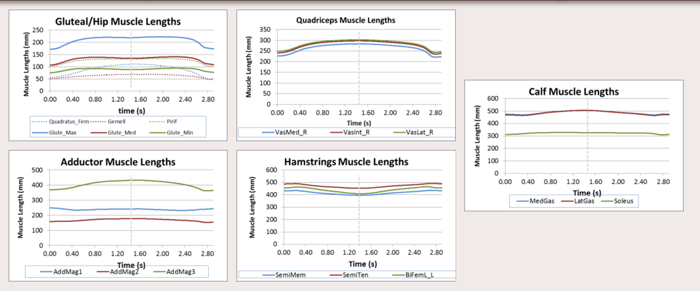
Joint Forces
- Calculated forces at the body segment joints
- Indicate loading on key skeletal segments
- Inform bone adaptation models



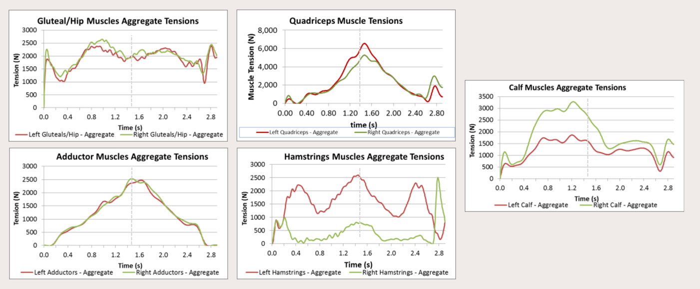
Muscle Data

- Key muscles of interest: Gluteals/Hip, Quads, Adductors, Hamstrings, Calves

Muscle Lengths
- Calculated contractile length histories for select muscles
- Indicate the muscle kinematic behaviors and range of motion
- Right/Left agree within ±2%
- Gray dashed lines indicate transition from descent/ascent

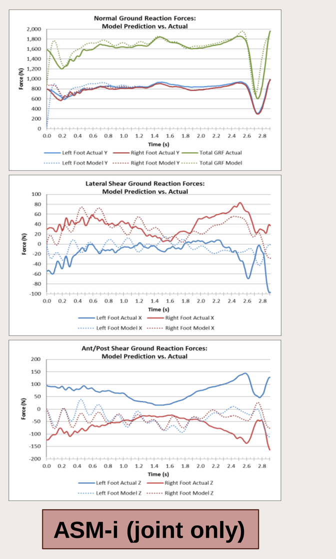


Muscle Tensions
- Calculated tensile forces in the primary muscle actuators
- Indicate the contributions of specific muscle groups, but not necessarily individual muscles within groups
- Inform the DAP muscle adaptation model

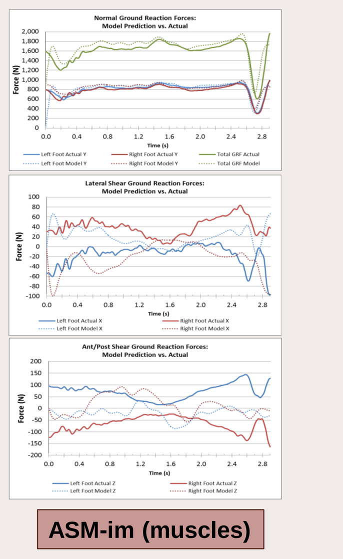


Ground Reaction Forces (GRF) - Verification

- Compare model-predicted GRF data with measured GRF



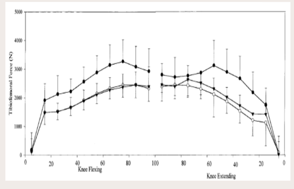
ASM-i (joint only)



ASM-im (muscles)

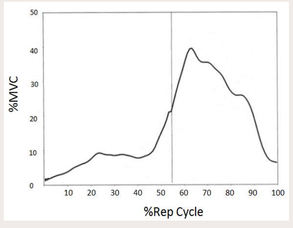
Validation by comparison with the literature

Compare model-calculated joint angles, torques and forces with reported data



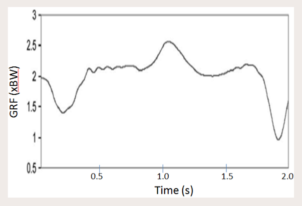
Tibiofemoral compressive force during a barbell squat[4] compares well with calculated Y axis knee forces (with sign inverted).

Compare model-calculated muscle tension vs. reported relative muscle activation via EMG



Rectus femoris measured EMG during barbell squat[5]. Profile shape compares with calculated muscle tension profiles but the asymmetry between descent and ascent is not fully captured by the model.

Compare measured and model-calculated GRF's with reported GRF data



GRF profile measured for fast-cadence squat[3] compares well with both measured and calculated GRF for this effort

DISCUSSION: ACCOMPLISHMENTS AND FINDINGS

Accomplishments to date

- Completed integrated modules for the 1g squat exercise in both joint-only (ASM-i) and muscle/joint (ASM-im) configurations.
- Verified kinematics, joint forces/torques, muscle lengths and GRF
- Validated model kinematics, dynamics and GRF's versus literature on the squat exercise
- Performed preliminary sensitivity analysis to quantify effects of perturbations to model parameters
- NASA-STD-7009 credibility assessed for 1g, estimated for 0g

Major Findings

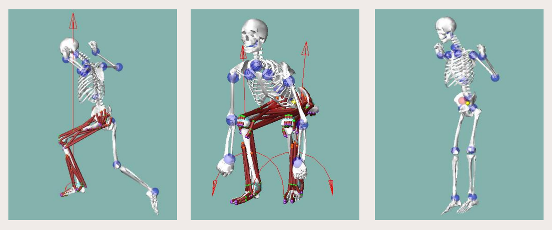
- Kinematic agreement is better during the ascent/descent phases than at the start/end of the movement
- Joint forces are more accurately reproduced in the ASM-im model than the ASM-i
- Relative muscle tensions among muscles mimic the activation patterns reported in the literature.
- The 0g kinematics cannot be predicted by simply ignoring gravity and activating the VIS on the ARED.

FUTURE WORK

Enhance ARED Squat Model

- Obtain 0g motion capture data from ISS video to fully develop 0g ARED squat model
- Quantify the effects of 0g and the VIS on exercise kinematics and dynamics
- Analyze effects of posture, positioning and cadence on module outputs (kinematics, joint forces/torques and muscle tensions)
- Overcome limitations in the 1g model such as small data set, artifacts and absence of upper body musculature

Model Other Exercises on ARED



Single-leg Squat | Deadlift (muscle model) | Heel Raise

Inform Musculoskeletal Adaptation Models

- DAP Bone Adaptation Model
  - Provide exercise-induced loading inputs
  - Key skeletal sites: hip, spine and femoral neck
- DAP Muscle Adaptation Model[12]
  - Change LifeMOD muscle parameters to reflect adaptations to spaceflight
  - Quantify effects of changes to cross-sectional area, maximum isometric force and pennation or individual muscles on overall performance

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